ASSESSING HYDROLOGICAL IMPACTS OF THE GILGEL GIBE III DAM ON LAKE TURKANA WATER LEVELS

by
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ABSTRACT

Lake Turkana is a saline, endorheic lake in northern Kenya and is the fourth largest lake in Africa. The lake receives 90% of its inflow from Ethiopia's Omo River. Local pastoralists who live near the lake are increasingly reliant on Lake Turkana fisheries for subsistence as frequent droughts in the region limit the amount of productive land for livestock. Fisheries within the lake are dependent on annual flood pulses from the Omo River and are generally more productive with greater lake volume. In the past several years, there have been hydrological impacts in the Omo River basin, namely the building of a series of hydroelectric dams. This study will use satellite derived data to assess the hydrological impacts of the largest of these developments, the Gilgel Gibe III Dam. Observed changes in lake volume will be derived from lake height altimetry data. These observed changes will then be compared to predicted changes in lake volume derived from a naturalized, basin-scale water balance. Findings suggest that although the Gilgel Gibe III Dam is likely having an effect on the timing of Lake Turkana's seasonal floods, the dam may not be fully responsible for the overall volume decrease seen in the lake since dam construction was completed in 2015.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALEXI	Atmospheric Land Exchange Inverse model
CHIRPS	Climate Hazards Infrared Precipitation with Station data
FLDAS	Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System
G-REALM	Global Reservoirs and Lakes Monitor
Gibe III Dam	Gilgel Gibe III Dam
km	kilometer(s)
km^2	square kilometer(s)
km^3	cubic kilometer(s)
m	meter(s)
mm	millimeter
mm/yr	millimeter per year
SRTM	Shuttle Radar Topography Mission
WWF	World Wildlife Fund

1. INTRODUCTION

Since a 1996 master plan first identified major hydropower and irrigated agricultural opportunities in Ethiopia's Omo River basin, there have been concerns about what effect these developments might have downstream on Kenya's Lake Turkana (Woodroofe et al., 1996). One such plan that has come to fruition, the Gilgel Gibe III Dam (Gibe III Dam), is the subject of this study. Since the dam's completion in 2015, there have been reports that the regulation of flow from the dam has "eliminated the annual flood pulses of the (Omo) River", and that the filling of the reservoir has "reduced the water level in Lake Turkana" (Hodbod et al. 2019). But how can we be certain that these hydrologic impacts were caused by the dam itself and not other impacts in the basin? And are these changes in Lake Turkana water levels driven by anthropogenic impacts or climatic conditions? This study seeks to discern what is driving observed volume changes in Lake Turkana by characterizing lake volume change from satellite altimetry data and conducting a basin-scale water balance from satellite-derived data.

Avery (2010, 2012, and 2013) assessed the expected hydrological impacts of developments within Ethiopia's Omo basin on Lake Turkana's water levels and fisheries. These studies warn of not just the filling of Gilgel Gibe III (Gibe III) reservoir, but also the impacts of planned large-scale irrigation schemes in the lower Omo River valley that would now be possible due to regulated flow sequence from the dam. He predicted that up to 50% of the lake's inflow from the Omo River could be abstracted by irrigation alone, leading to a drop in lake levels of 20 meters (m). He also predicted that the filling of the Gibe III reservoir alone would cause a two-meter drop in Lake Turkana's surface level.

Avery (2010) also developed a lake-scale water balance model to assess the impacts of developments within the Omo River basin on Lake Turkana water levels. This model used satellite radar altimetry to generate lake inflow discharges directly from changes in lake level. It was assumed that water loss in the lake is driven by relentless evaporation off the lake surface. Analysis of resulting flow duration curves for the Omo River confirmed that the Omo's 'natural' low flows are insufficient to sustain large-scale agriculture. Therefore, without controlled flows from the Gibe III dam, large-scale irrigation schemes would not be feasible.

Velpuri et al. (2011) developed a model for Lake Turkana water levels using a multi-source satellite derived dataset, and validated the results using satellite altimetry data. Their analysis indicated that fluctuations in Lake Turkana water levels were mainly driven by lake inflows and evaporation over the lake's surface. The model showed seasonal variations in Lake Turkana water levels of 1-2 m.

The first objective of this study is to use satellite-based lake height altimetry to characterize Lake Turkana water levels before and after construction of the Gibe III Dam. This dataset will also be used to quantify associated changes in lake volume. The second objective is to develop a naturalized basin-scale water balance of the Lake Turkana basin to determine what lake volume changes can be expected due to climatic conditions in the basin. A final objective is to quantify and describe any water abstraction upstream in the basin, either from the Gibe III reservoir or from water withdrawal for irrigation.

2. STUDY AREA

The study area consists of the catchment basin of Kenya's Lake Turkana (**Figure 2-1**). This basin covers 150,000 square kilometers (km^2), with approximately half its area in Ethiopia, half in Kenya, and small encroachments into Uganda and South Sudan (Lehner et al., 2008). The primary river system in this basin is the Omo River, which accounts for 90% of the inflow into Lake Turkana (Ferguson & Harbott, 1982). The Omo River begins in the highlands of Ethiopia and drains southward for approximately 760 kilometers (km) before terminating in Lake Turkana. While the headwaters of the Omo River start in the in the relatively wet highlands of Ethiopia, it ends in an area of extreme aridity around Lake Turkana. Other major river systems within this basin include the Turkwell and Kerio Rivers. Both of these systems originate in the Southern portion of the basin and account for approximately 25% of the Turkana drainage area, but less than 10% of the total water discharge into Lake Turkana (Hirpa et al., 2018; Ferguson & Harbott, 1982).

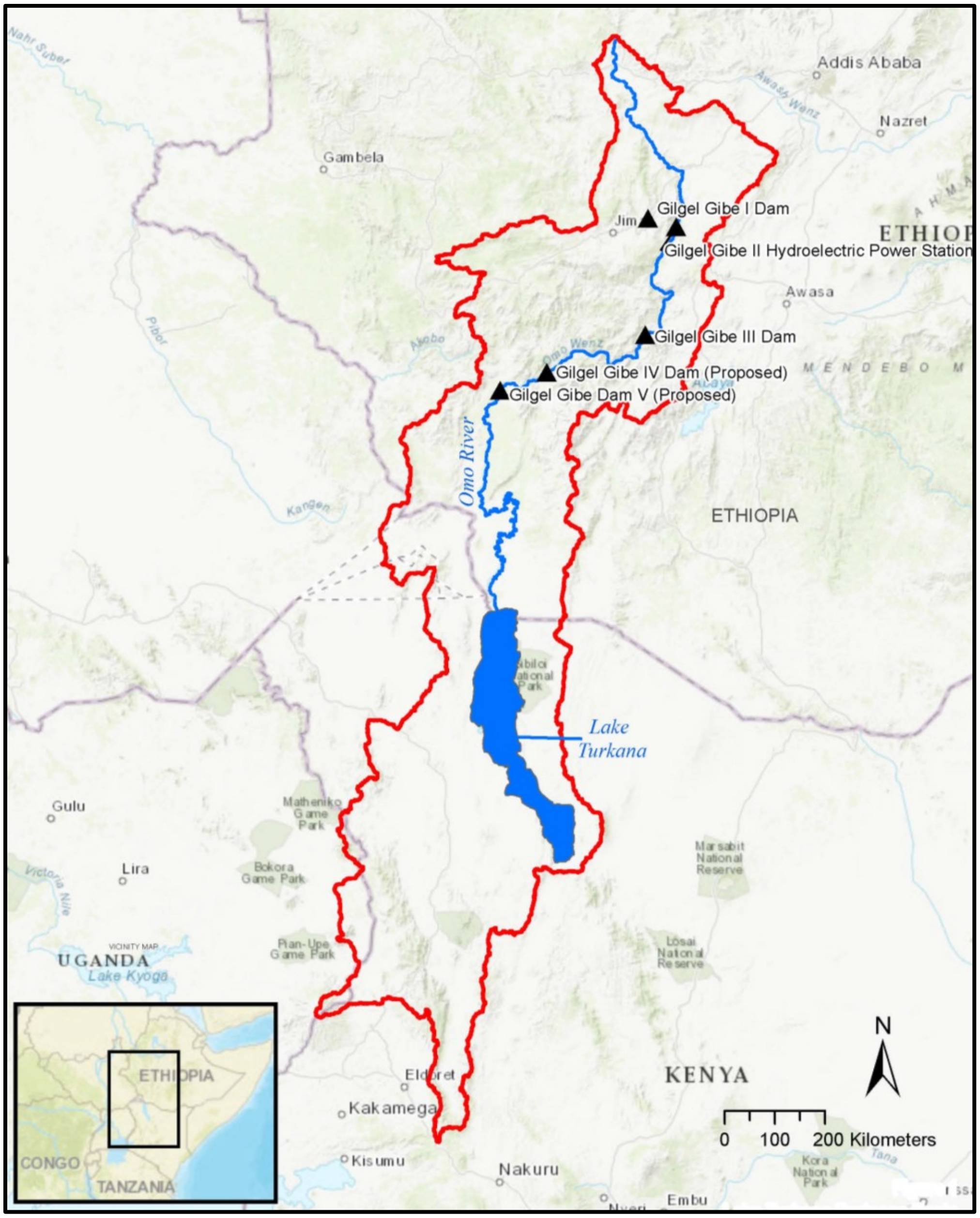

Figure 2-1: Study area

2.1. LAKE TURKANA

Lake Turkana is the fourth largest lake in Africa and the largest desert lake in the world. Its surface area is approximately 7,570 km^2, and its average width is 32 km. The most recent bathymetric survey of the lake was conducted in the mid-1970s. The survey found an average lake depth of 30 meters and a maximum depth of 114 m, found at the lake's southern end (Kallqvist et al., 1988). Lake Turkana is an endorheic lake, meaning it is the terminal lake of a closed basin that has no outflow (Avery 2010). Hence, all inflow eventually evaporates from the lake surface over time. As water evaporates off the lake surface, minerals are left behind, causing the lake water to be brackish with a salinity of about 2500 parts per million (Johnson & Malala, 2009). This salinity level is considered to be significantly unpalatable according to World Health Organizations drinking water quality standards (WHO, 2006). The lake's high fluoride concentration is also a concern, exceeding acceptable health standards and causing varying levels of fluorosis (Avery, 2013). Nevertheless, people and livestock still drink the lake water due to the absence of alternative potable water sources (ibid.).

Lake Turkana's hydrology is driven primarily by inflow from the Omo River and evaporation off the lake surface. Seasonal floods facilitate recess agriculture along portions of the lower Omo's riverbanks (Avery, 2013). The river's flood pulses also raise Lake Turkana water levels, diluting the lake's brackish waters and inundating lake margins, which provide habitat for breeding fish (Avery, 2013). Flow rates are available for the lower Omo River at Omarate, Ethiopia, but only from 1977 to 1980 (ibid.).

In general, the wet season in the Lake Turkana basin is from April to October, with peak rainfall typically seen in April (Funk et al, 2015). However, it should be noted that rainfall patterns differ substantially across the basin from the tropical, humid climate in the Ethiopian Highlands in the north to the hot, arid semi-desert climate in the south. Annual precipitation varies from approximately 1,900 millimeters per year (mm/yr) in the northern expanses to less than 300 mm/yr in the southern regions (Woodroofe et al., 1996). Additionally, northern areas display a uni-model wet season with peak rainfall in July, while southern areas display a bi-modal wet season with peak rainfall in April and October (Avery, 2010).

The area around Lake Turkana is sparsely populated with indigenous groups who speak various languages. According to Kenya's 2009 population census, approximately one million people live in the Administrative Districts around Lake Turkana (Avery, 2012). These groups have traditionally practiced agro-pastoralism. However, periodic drought and rapid overpopulation over the past several decades have made full reliance on pastoralism infeasible. Food shortages have made the area reliant on food aid, which accounted for up to 75% of average food intake around the lake (Brewin, 2009). As recently as 2019, the Kenyan counties bordering Lake Turkana, Marsabit and Turkana, are facing acute food insecurity (USAID, 2019). In response to these food shortages, the Kenyan government has encouraged alternative livelihoods, and people in the region have turned to irrigation farming along incoming rivers and fishing in the lake. Today, fishing activities are widespread around the lake, and fish have become a critical food source for the people living around Lake Turkana. In addition, pastoralists have moved their livestock closer to Lake Turkana in order to use it as a water source (Carr, 2016).

Despite the lack of an outlet and high salinity, Lake Turkana supports over 50 freshwater fish species (Malala, 2017). The lake has mainly Nilotic species, thanks to a former fluvial connection with the Nile River basin, and some endemic species (Hopson et al., 1982). The Nile perch, one of the world's largest freshwater fish, and many types of cichlid fish are valuable food sources for populations around the lake.

Many species of lacustrine fish rely on periodic fluctuations in water levels to spur spawning and increase available habitat in littoral waters (Kolding, 2010). Maintaining total lake volume is also important for fisheries, as volume reduction can lead to a decrease in available habitat and an increase in water salinity. The most productive fishery in the lake, Ferguson's Gulf, is located on the western shore of the lake and is particularly susceptible to drying up when lake levels drop (Hopson et al., 1982).

2.2. IMPACTS IN THE OMO RIVER VALLEY

In 1996, a master plan was developed for the Omo River basin and identified major hydropower and irrigated agriculture opportunities (Woodroofe et al., 1996). The "Gibe-Omo hydroelectric cascade" is one such development that has come to fruition in the last several decades. This project consists of a series of hydroelectric projects upstream of Lake Turkana along the Omo River and its tributaries. The dams' implementation would greatly increase Ethiopia's power generating capacity and provide water for largescale irrigation schemes. These hydroelectric projects include: the Gilgel Gibe I Dam (completed in 2004), the Gilgel Gibe II Hydroelectric Power Station (completed in 2009), the Gilgel Gibe III Dam (completed in 2016), and the Gilgel Gibe IV and V dams (proposed) (Salina Impregilo, no date). The primary focus of this study will be on the effects that the Gibe III Dam has had on Lake Turkana's hydrology.

Located approximately 600 km upstream of Lake Turkana, the 240 meter (m) high Gibe III Dam has a generating capacity of 1,870 megawatt (SOGREAH Consultants, 2010). In 2009, the African Development Bank first considered financing this project, but they withdrew when an initial hydrological study revealed the major hydrological and ecological impacts the dam would have on Lake Turkana and associated irrigation development downstream (Avery, 2013). Subsequently, Chinese donors stepped in to finance the project. Construction began on the dam in 2006 and was completed in mid-2015, after which the reservoir behind the Gibe III Dam began to fill. The reservoir's storage capacity was expected to be 14.7 cubic kilometers (km^3) at maximum level, including 2.95 km^3 of dead volume and 11.76 km^3 of active volume (SOGREAH, 2010). The Gibe III Dam controls approximately 50% of the Omo River's catchment area and 70% of the basin's total water runoff (ibid.).

Beginning in 2011, the state-owned Ethiopian Sugar Corporation began implementing a plan to create over 100,000 hectares of irrigated land for sugar cane production along the lower Omo (Kamski, 2016). This 'Omo-Kuraz Sugar Development Project' plans to enable large-scale sugarcane development to support four new sugar factories, two of which have been completed to date (Sugar Corporation, 2019). According to the Ethiopian Sugar Corporation, there is currently a coffer dam and canal network in the Lower Omo, which supports 30,000 hectares of irrigated land, 16,000 of which is currently cultivated with sugarcane. Along with assessing impacts directly from Gibe III Dam, this study will also investigate the water demand from this irrigation development.

3. DATA AND METHODS

3.1. DATA

For this study, seven satellite-derived datasets were used: (1) United States Department of Agriculture Global Reservoir/Lake Monitor (G-REALM) lake surface elevation data, (2) Climate Hazards Infrared Precipitation with Station data (CHIRPS), (3) Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS), (4) Atmospheric Land Exchange Inverse (ALEXI) model, (5) World Wildlife Fund (WWF) HydroBASINS, (6) Shuttle Radar Topography Mission (SRTM) digital elevation model, and (7) LANDSAT aerial imagery. **Table 3-1** summarizes the various satellite-derived datasets used in this study.

Table 3-1: Satellite-derived datasets used in this study

No	Source	Parameter(s)	Frequency	Resolution	Reference
1	USDA G-REALM	Lake surface elevation	10-day	Not Applicable	(USDA Foreign Agricultural Service, 2019)
2	CHIRPS	Precipitation	Daily	0.05° × 0.05°	(Funk et al., 2015)
3	FLDAS	Evapotranspiration, soil moisture, surface pressure, specific humidity, radiation and air temperature	Daily	0.05° × 0.05°	(McNally et al., 2017)
4	ALEXI	Evapotranspiration	7-day	10 km	(Mecikalski et al., 1999)
5	WWF HydroBASINS	Drainage basin delineation	Single date	500 m	(Lehner et al., 2006)
6	SRTM	Digital elevation model	Single date	30 m	(Farr & Kobrick, 2000)

Lake surface elevation data for both Lake Turkana and the Gibe III reservoir were provided by the United States Department of Agriculture Global Reservoir/Lake Monitor (G-REALM) (USDA Foreign Agricultural Service, 2019). This dataset utilizes radar altimetry data from the Jason-3, Jason-2/OSTM, Jason-1, TOPEX/Poseidon, and ENVISAT missions that make periodic passes over inland lakes and reservoirs. The diameter footprint of the ranging depends on surface roughness and can extend from 200 meters to a few kilometers. Estimated error ranges from 0.042 m to 0.063 m for Lake Turkana and from 0.042 m to 1.17 m for the Gibe III reservoir. Lake surface elevations have a repeat period of 10 days and are provided as meters above mean sea level.

CHIRPS is a quasi-global rainfall dataset provided by the University of Santa Barbara (Funk et al., 2015). The dataset incorporates both satellite data and rain gage data. This study uses the high resolution (0.05° × 0.05°) daily Africa rainfall dataset. In comparison with rain gage data at 1,200 stations in East Africa, the CHIRPS product has a mean error of 26.5 millimeters (mm) over Ethiopia and 31.6 mm over Kenya (Dinku et al., 2018). Similarly, in comparison with the gage-based Global Precipitation Climatology Centre reference precipitation product, CHIRPS has a wet season mean error of 79 mm per 3 months over Africa (Funk et al., 2015).

The FLDAS model is based on the Noah 3.3 Land Surface Model for East Africa, which includes three components: canopy intercepted evaporation, transpiration from canopies, and evaporation from bare soil (McNally et al., 2017). CHIRPS precipitation data is used as the meteorological input for the FLDAS model. The data have 0.10-degree spatial resolution, and this study used monthly data for the following parameters: evapotranspiration, soil moisture, surface pressure, specific humidity, radiation, and air temperature.

The ALEXI model is a coupled two source (soil and canopy) land-surface model with an atmospheric boundary level model. The model derives evapotranspiration estimates that are driven by thermal infrared remote sensing inputs and normalized difference vegetation index information (Mecikalski et al., 1999). No precipitation data or moisture storage capacity is required to run the model. The data has a 10 km resolution and is available at 7-day intervals. ALEXI data was used in this study to detect irrigation signals across irrigated areas of the Omo River basin.

The Lake Turkana basin shapefile was provided by HydroSHEDS, a mapping product that provides hydrographic information at regional and global scales (Lehner et al., 2006). Developed by the Conservation Science Program of the World Wildlife Fund, these data are based on high resolution elevation data obtained during NASA's Shuttle Radar Topography Mission. Drainage basins from HydroSHED have a spatial resolution of approximately 500m.

The Shuttle Radar Topography Mission was flown aboard the shuttle *Endeavor* in February 2000 and used interferometric radar to create the first near-global set of land elevations (Farr & Kobrick, 2000). For this study, the 'void filled' SRTM elevation data was used to calculate the actual volume of water stored within the Gibe III reservoir. The SRTM data has a 30 m resolution.

3.2. METHODS

In order to calculate the observed change in storage for both Lake Turkana and the Gilgel Gibe III reservoir, I used lake surface altimetry data and assumed a cylindrical lake volume. The calculation for observed change in lake storage is:

$$\Delta S_{l,observed} = \Delta h A_l$$

where:

$\Delta S_{l,observed}$ = *Observed change in lake storage*

Δh = *Change in lake height from month to month*

A_l = *Surface area of lake*

The most recent available bathymetric data available for Lake Turkana is from the mid-1970s and was therefore considered too old to be used for this study (Hopson, 1982). I digitized the surface area of the lake using current aerial imagery.

Next, I conducted a comprehensive water balance of the Lake Turkana basin. This is a naturalized water balance, meaning that it accounts for all basin inputs and outputs as if the basin were unimpacted. Anthropogenic impacts, such as irrigation and groundwater withdraw, are not included in this naturalized water balance.

Inputs include precipitation across the entire basin (i.e., over both land and water), and outputs include the change in soil moisture throughout the basin's land area, evapotranspiration across the basin's land area, and evaporation off the lake surface:

$$\Delta S_{l,predicted} = P - SM - ET_b - E_l$$

Where:

P = Precipitation over basin and lake

SM = Change in soil moisture (looking backwards in time)

ET_b = *Evapotranspiration over basin*

E_l = *Evaporation off lake surface*

$\Delta S_{l,predicted}$ = *Predicted change in lake storage*

While some groundwater movement in and out of Lake Turkana is expected, this quantity is not measurable. Regardless, these seepage losses from the lake are expected to be minimal (Yuretich and Cerling, 1983). Apart from evaporation off the lake surface (E_l), data sources for water balance parameters are shown in Table 3-1 and were taken as averages across the basin area.

To estimate evaporation off the lake surface (E_l), I used the Complementary Relationship Lake Evaporation (CRLE) model (Morton et al., 1985). The FLDAS model provided the meteorological forcing inputs for the CRLE model, which included relative humidity, temperature, and solar radiation. Developers validated the CRLE model results with lake evaporation derived from water balances for seventeen lakes. On an annual basis, the model results were within seven percent of the water balance results.

The resulting predicted change in lake storage (ΔS_l) was too variable to discern long-term trends, likely due to the inconsistent timeframes of the dataset (e.g., precipitation was taken as a monthly total and soil moisture was taken as a difference in soil moisture from month to month, looking backwards). Therefore, a 3-month moving average of the predicted lake storage change was used to smooth out the short-term fluctuations.

To characterize the timing of the filling of the Gibe III reservoir and the subsequent water surface elevation patterns following filling, I analyzed G-REALM lake surface elevation for the reservoir from January 2014 to December 2018. To estimate the current capacity of Gibe III reservoir, I used the Surface Volume tool in ArcMap 10.7. Inputs for the tool include water surface elevation at a given point in time, provided by G-REALM lake surface elevation, and land elevation data, provided by SRTM. I calculated reservoir volume in October 2016, when the reservoir reached full capacity, and in June 2019, at a typical annual minimum. I compared reservoir volume, especially during the initial filling period, to changes in volume variation in Lake Turkana.

Finally, I used current aerial imagery of the Lake Turkana basin to delineate areas of visible cultivation along the Lower Omo River valley. Then, I averaged the annual ALEXI evapotranspiration signal across the area of visible cultivation from several years before the appearance of cultivated land to 2016. The resulting evapotranspiration signal represents the observed water demand for that irrigated area.

4. RESULTS AND DISCUSSION

4.1. LAKE TURKANA WATER SURFACE ELEVATION AND VOLUME VARIATION

Figure 4-1 presents water surface elevations (in meters above mean sea level) of Lake Turkana for every 10-day altimetry measurement from January 2000 to December 2018. Error for each measurement was provided by G-REALM and ranged from 0.042 m to 0.105 m, with an average error of 0.043. Error bars are displayed for each data point in **Figure 4-1**.

For reference, two approximate dates are displayed in both **Figure 4-1** and **Figure 4-2**: (1) Beginning of filling of the Gibe III reservoir in mid-2015, and (2) Inauguration of Gibe III Dam in in December 2016. Once the dam was inaugurated, it is assumed that the dam's hydroelectric station was fully operational. However, this point does not necessarily indicate the completion of filling of the reservoir. A detailed description of the filling of Gibe III reservoir and its estimated capacity is described in Section 4.4.

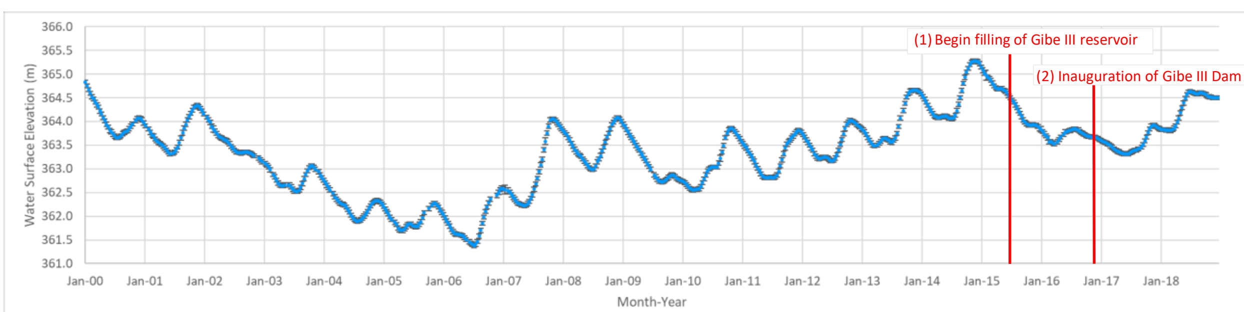

Figure 4-1: Lake Turkana water surface elevation

From 2000 to 2006, there was a decreasing trend in water surface elevation from an annual average of 364.05 m in 2000 to an annual average of 361.83 m in 2006. From 2006 to 2014, there was an increasing trend in water surface elevation, which peaked in 2014 with an annual average of 364.51 m. Before filling of the reservoir commenced, these data show a pattern of annual peak lake surface elevations between September and November for most years. Exceptions include 2002 and 2009, which saw negligible peaks during these months. During the filling of the reservoir, there was a cessation of annual peaks and a general decline in lake surface elevation from early 2015 to mid-2017. From mid-2017 through 2018, lake levels were on the rise, and began to display annual peaks, albeit less pronounced than pre-dam conditions.

Monthly volume variations for Lake Turkana characterize hydrological trends at monthly timescales, which can then be compared to monthly satellite-based data and model products. To calculate lake volume variation, I assumed a cylindrical volume and multiplied monthly changes in water surface elevation by the average surface area of the lake. Likewise, I estimated error in monthly volume variation as the error in lake surface elevation multiplied by the surface area of the lake. **Figure 4-2** presents estimated lake volume variations and associated error from January 2000 to December 2018.

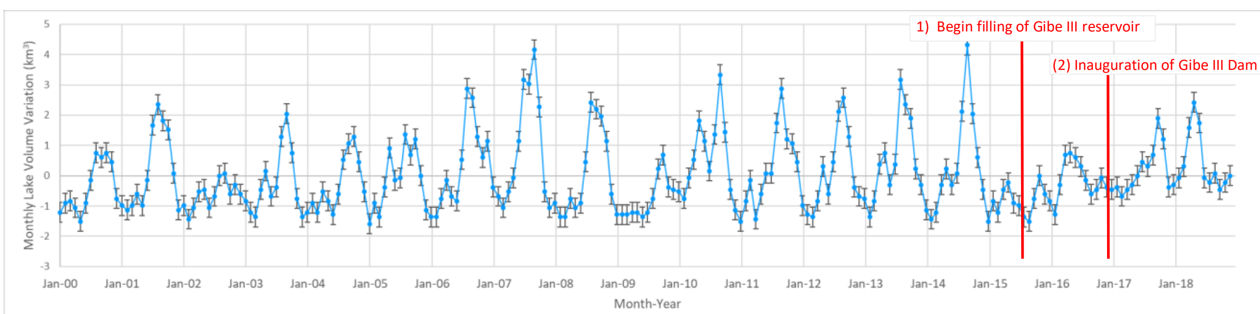

Figure 4-2: Lake Turkana monthly volume variation

Historical monthly volume variation of Lake Turkana generally mirrors changes in lake surface elevation shown in **Figure 4-1**. Wet months, denoted by positive lake volume variation, are typically seen from July to November. Dry months, denoted by negative lake volume variation, are typically seen from December to April. Prior to filling of the Gibe III reservoir, noticeably drier years occurred in 2002 and

2009, where there are only one or two months of positive lake volume variation. In 2015, the year that Gibe III reservoir began filling, Lake Turkana did not see any months with positive lake volume variation, meaning that lake volume was in decline for all months. In 2016, while the reservoir was still being filled, the wet months occurred earlier (April to July) and were smaller in magnitude. In 2017, Lake Turkana displayed volume variation more consistent with historical trends (wet months from July to November). However, in 2018 wet months are again seen much earlier (March to June) than historical trends.

To track annual trends in the volume of Lake Turkana, I summed monthly lake volume variations for each year from 2000 to 2018. **Figure 4-3** presents these annual lake volume variations and associated error.

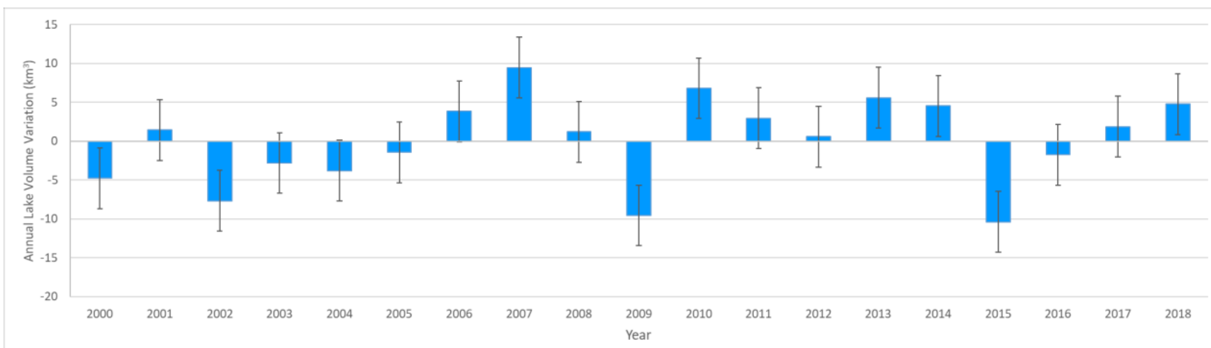

Figure 4-3: Lake Turkana annual volume variation

The 18-year change in lake volume variations for Lake Turkana sums to +1.06 km^3, indicating the lake has had a net increase in volume since 2000. Prior to the filling of Gibe III reservoir (2000 to 2014), Lake Turkana saw an overall volume increase of 1.36 km^3. In contrast, following the filling of the reservoir (2015 to 2018), Lake Turkana saw an overall decrease of 0.30 km^3 in volume. The three wettest years were 2007, 2010, and 2013, with a volume increase of 9.46 km^3, 6.81 km^3, and 5.60 km^3, respectively. The three driest years were 2002, 2009, and 2015, with a volume decrease of 7.65 km^3, 9.54 km^3, and 10.37 km^3, respectively.

To quantify trends in seasonal flooding of Lake Turkana, I averaged monthly lake volume variations across all years. **Figure 4-4** displays average monthly lake volume variations for Lake Turkana from 2000 to 2018 and associated error.

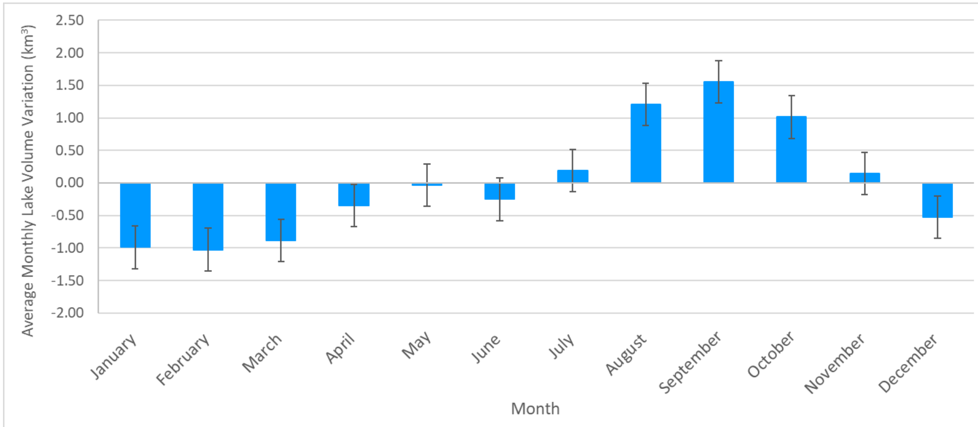

Figure 4-4: Lake Turkana average monthly volume variation (2000 to 2018)

The average monthly lake volume variations in **Figure 4-4** illustrate the historical seasonal flooding patterns of Lake Turkana. On average, Lake Turkana is losing volume from December to June and gaining volume from July to November. The driest months are January and February, with average monthly losses of 0.99 km^3 and 1.02 km^3, respectively. In contrast, the wettest months are August and September, with average monthly gains of 1.21 km^3 and 1.55 km^3, respectively. These shifts in average monthly lake volume correspond with the wet season (April to October) and dry season (November to March) in the Turkana region, and indicated a one- to two-month response of lake volume to precipitation.

To determine the downstream effects Gibe III Dam may have had on Lake Turakana, I compared average monthly lake volume variation before the construction of Gibe III Dam (January 2000 to June 2015) and after construction (July 2015 to December 2018). Based on media reports and lake height altimetry data, the reservoir behind Gibe III Dam began filling in mid-2015 and became fully operational in December 2016 ("Ethiopia", 2016; USDA, 2019). **Figure 4-5** presents average monthly lake volume variations before and after construction of the Dam (i.e., before and after the reservoir behind Gibe III Dam began filling).

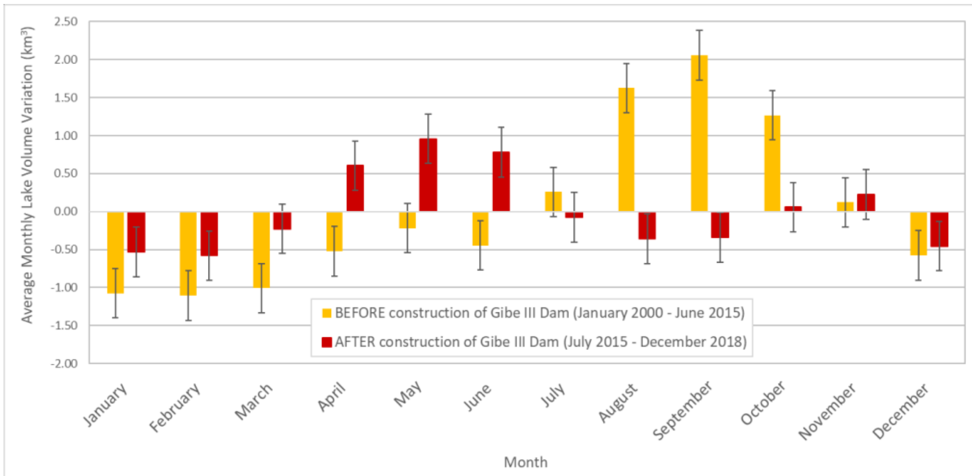

Figure 4-5: Average monthly volume variation before and after construction of Gibe III Dam

Before construction of the dam, seasonal floods were of greater magnitude and occurred from August to October. Following construction of the dam (and subsequent filling of the reservoir), floods were nearly half the magnitude seen in pre-dam conditions and occurred approximately four months earlier, from April to June. Likewise, periods of negative volume variation were also smaller in magnitude, indicating the dam had a moderating effect on Lake Turkana water levels.

4.2. NATURALIZED WATER BALANCE OF LAKE TURKANA BASIN

4.2.1. Individual Components

Individual components of the naturalized water balance of Lake Turkana basin are presented in **Figure 4-6** at monthly timesteps from January 2000 to December 2018. The monthly precipitation volume includes precipitation across all of Lake Turkana basin (both over land and over the lake surface), while monthly evapotranspiration volume includes evapotranspiration across only the land surface in the basin. Change in soil moisture is calculated across the basin's land surface by taking the difference in month-to-month basin soil moisture storage, looking backwards in time. Evaporation off the lake surface is simply the estimated volume of water evaporated from the wetted lake surface.

Error for all individual components of the naturalized water balance was estimated to be 3.96 km^3. This estimate is based on the reported accuracy of CHIRPS precipitation data, of which all FLDAS model parameters are based on.

Figure 4-6: Individual components of Lake Turkana water balance

As shown in **Figure 4-6**, the component of the water balance with the largest magnitude is precipitation, peaking from 10 km^3 to 35 km^3 for 4 to 6 months during the summer wet seasons. Minimum monthly precipitation is typically below 5 km^3 from December to February of each year. Evapotranspiration is directly correlated with patterns in precipitation, with substantial changes in evapotranspiration occurring up to one month after large shifts in precipitation. However, the magnitude of evapotranspiration is much less during the summer wet season, peaking from 8 km^3 to 15 km^3 for 4 to 6 months. In contrast, during the drier months from December to February, monthly evapotranspiration is slightly larger than monthly precipitation. Changes in soil moisture, although highly variable, appear to be correlated with precipitation, with positive values during months of high precipitation and negative values during months of low precipitation. Evaporation off the lake surface is small in magnitude relative to the other individual parameters, never reaching over 2 km^3, even during summer months.

4.2.2. Predicted Volume Variation

The predicted change in lake storage resulting from the naturalized water balance, hereafter referred to as the predicted volume variation, is show in **Figure 4-7** as both monthly and quarterly averages along with estimated error. This value, given as a total volume in km^3, represents the expected volume change in Lake Turkana if the basin was unimpacted by anthropogenic factors.

As shown in **Figure 4-7-a**, the monthly predicted volume variation is highly variable, jumping up and down from month to month without any discernable long-term trend. This is likely due to the inherent uncertainty in satellite-based data and model products, and the mismatch in timescale for some of the parameters. For example, precipitation, evapotranspiration, and evaporation are all measured as monthly averages, while soil moisture is measured as the monthly change in total soil moisture storage, looking backwards to the previous month. Furthermore, the variability of the predicted volume change is reflected in the high variability of some of the water balance parameters, namely soil moisture and precipitation.

To smooth the water balance, I took a 3-month running average of the predicted volume variation. This time period was chosen to maximize signal-to-noise ratio and minimize discrepancy between the two temporal data types. This 3-month (quarterly) average of predicted lake volume variation is shown in **Figure 4-7-b**. These data show a much smoother trend with peaks in the 3-month period from July to August and valleys typically in either the period from January to March or from October to December. This is consistent with both meteorological trends and observed lake volume variation, as described in Section 4.1.

(a) Monthly

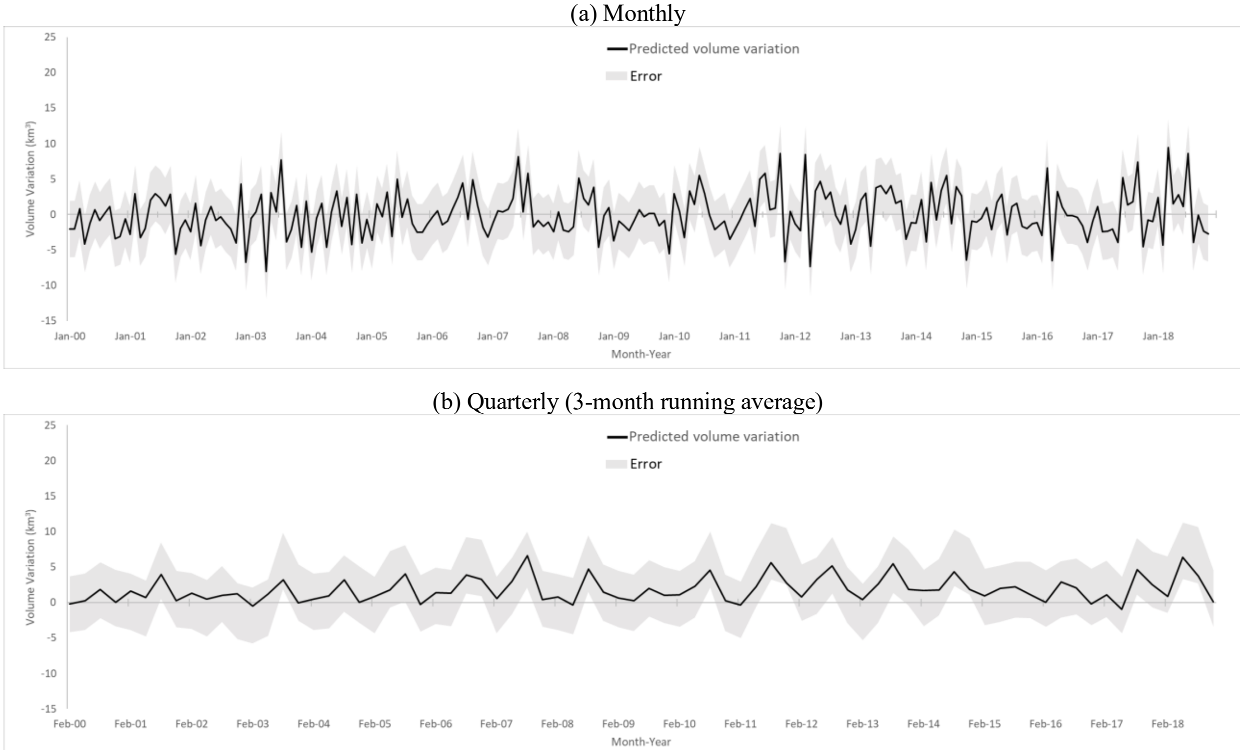

Figure 4-7: Residual of Lake Turkana water balance.

Although the relative trend seen in **Figure 4-7** is reasonable given existing knowledge about the basin's climate, the magnitude is too high to be a reasonable estimate of the predicted change in lake storage. Nearly every residual data point is positive, indicating an implausible scenario of the lake gaining volume year after year. To correct for this bias, a reduction of 1.8 km^3 was applied to the predicted volume variation. This reduction was selected because it brought the average predicted volume variation down to

3.0×10^{-3} km^3, which is consistent with observed volume variation of Lake Turkana. The bias-corrected predicted volume variation will be used moving forward when comparing the predicted and observed change in lake storage.

4.3. COMPARISON OF PREDICTED AND OBSERVED VOLUME VARIATION IN LAKE TURKANA

To characterize the magnitude of upstream impacts on Lake Turkana, I compared two sources of lake volume variation: (1) the observed volume variation based on water surface altimetry, and (2) the predicted volume variation based on the basin-scale water balance. Any substantial deviations between predicted and observed change in lake volume may indicate anthropogenic impacts upstream. Namely, if the water balance predicts that Lake Turkana will increase in volume, but the observed lake volume declines or stagnates, then one can infer that water may have been abstracted somewhere upstream (e.g., by a dam or from irrigation).

Figure 4-8 shows both the predicted and observed volume variation for Lake Turkana from January 2000 to December 2018. The data are given as 3-month averages. Although there are several time periods where the predicted and observed volume variations diverge, they show similar patterns of lake volume increase in the summer months and decrease in the winter months. The observed change in lake volume variation is typically of a smaller magnitude than what is predicted by the water balance.

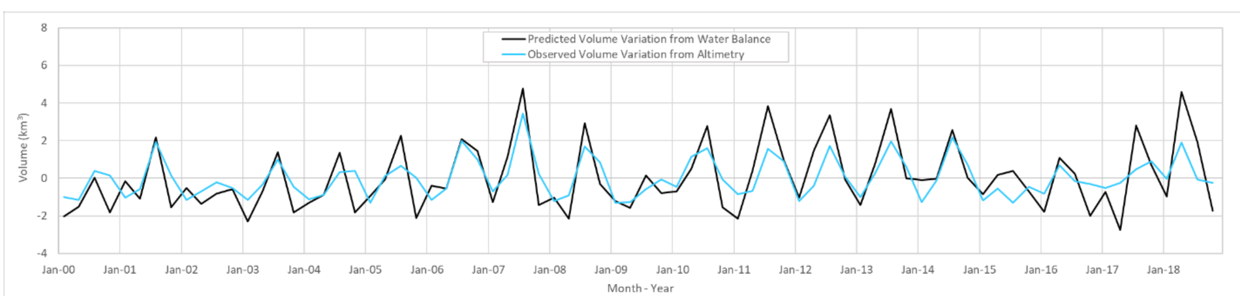

Figure 4-8: Observed and predicted volume variation in Lake Turkana (2000 – 2018)

Time periods of divergence between observed and predicted lake volume change may represent periods where upstream impacts are affecting Lake Turkana. As shown in **Figure 4-8**, 2015, the year that the

Gibe III reservoir began filling, shows a substantial difference between these two volume variation estimates. In mid-2015, the water balance predicted a very mild increase in lake volume, but instead Lake Turkana lost volume. By mid-2016, Lake Turkana is observed to have returned to its predicted annual flooding, but from late 2016 onward, there is again occurrences of deviation between the predicted and observed lake storage change. To look more closely into the period following the filling of Gibe III reservoir, **Figure 4-9** shows the annual predicted and observed lake volume variation from 2015 to 2018, and the difference in volume between the two.

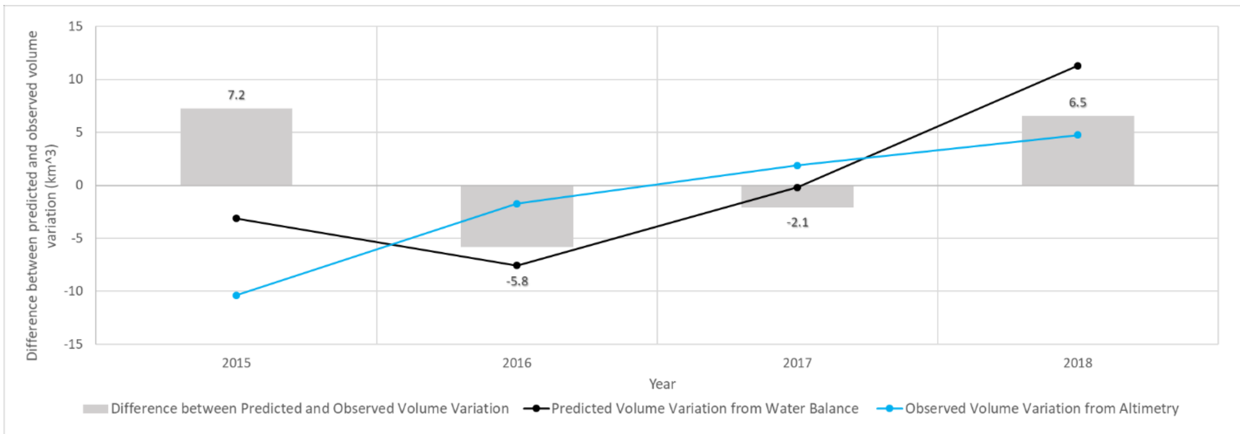

Figure 4-9: Observed and predicted volume variation in Lake Turkana (2015 – 2018)

In 2015, although both the predicted and observed volume variations were negative, the observed lake volume loss was 7.2 km^3 larger than what was predicted. This indicates that there may have been a volume of water of this magnitude abstracted during 2015. In contrast, in both 2016 and 2017, there was more volume variation than was predicted by the water balance. Finally, in 2018, although there was an overall positive volume variation, the predicted volume change exceeded the observed by 6.5 km^3, indicating again that there may have been water abstraction upstream, similar to 2015.

4.4. GILGEL GIBE III RESERVOIR CAPACITY

To characterize the filling of Gibe III reservoir and its subsequent management, I used lake surface elevation data to monitor the change in water levels from the dam's completion in 2015 through December 2018. **Figure 4-10** displays the water surface elevation every 9-10 days for this time period.

Estimated error associated with these data ranges from 0.042 m to 0.841 m, with an average of 0.190 m. The error is too small to show on the water surface elevation figure below.

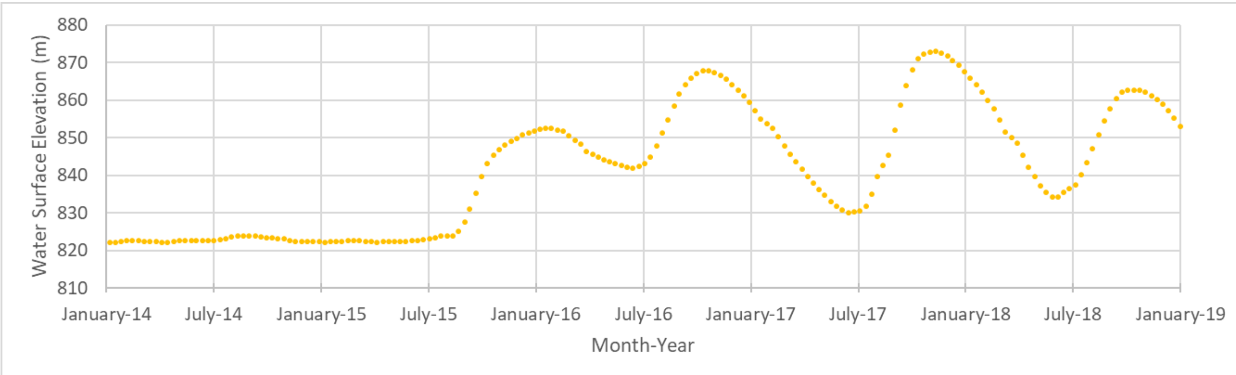

Figure 4-10: Gilgel Gibe III reservoir water surface elevation

As shown in **Figure 4-10**, prior to the commencement of reservoir filling in mid-2015, the altimetry measurements represent the ground elevation, approximately 823 m. Coinciding with the July 2015 dam completion date, the water surface elevation behind the dam began to rise rapidly. By mid-October 2015, the water surface elevation of the newly formed reservoir was 843 m, a 20 m rise from base-level conditions prior to dam construction. Water level rise continued, but at a slower rate, from mid-October 2015 to late January 2016, when it reached a local maximum of 852 m. The water level in the Gibe III reservoir declined at a steady rate through the first half of 2016, reaching a local minimum of 842 m in June 2016. In the second half of 2016, the water surface in the reservoir rose to a new maximum of 868 m by October 2016. Following this point, the water levels follow an annual cycle, with peaks in October/November and minimums in May/June. This annual cycle ranges from peaks between 860 m and 875 m to minimums between 830 m and 835 m.

Using the digital elevation model derived from SRTM, the volume of Gibe III reservoir was estimated at select water surface elevations. Based on the trend in water level fluctuations shown in **Figure 4-10**, it is assumed that the reservoir was at full capacity by October 2016, indicating that filling lasted just over one year. As previously stated, the minimum water surface elevation in the reservoir post-filling is between 830 and 835 m. Table 4-1 displays the estimated volume of Gibe III reservoir after filling was complete in

October 2016 (water surface elevation = 868 m) and at a typical annual minimum in June 2019 (water surface elevation = 830 m).

Table 4-1: Estimated volume of Gilgel Gibe III reservoir

Date	Elevation	Volume (km^3)	Surface Area (m^2)
10/23/2016	868	8.3	128.4
6/8/2017	830	4.1	83.0

As shown in **Table 4-1**, the reservoir's typical maximum capacity since it began filling in mid-2015 is approximately 8.3 km^3. At periods of minimum water levels, the reservoir's capacity is approximately 4.1 km^3. The reservoir's anticipated capacity was expected to be 14.7 km^3 at its maximum level, with 2.95 km^3 of dead volume and 11.76 km^3 of active volume (SOGREAH, 2010). Based on the estimated volume in Gibe III reservoir at an annual maximum water level, the reservoir is approximately 6 km^3 below its planned capacity. This indicates that there may be a potential for additional water abstraction behind the dam in the future.

4.5. IRRIGATION SIGNAL IN THE OMO RIVER VALLEY

To determine if irrigation activities in the Omo River valley were exerting a significant water demand on the Lake Turkana basin, I used ALEXI data to monitor evapotranspiration signal in the areas of the basin with cultivated land. Based on aerial imagery, there is an area of approximately 130 km^2 under cultivation in the lower Omo River valley. No other visible areas of cultivation were seen. The area that is currently under cultivation is support by a coffer dam and various canal networks and appeared in approximately 2013. **Figure 4-11** shows the total annual evapotranspiration across the visibly cultivated area from 2003 to 2016.

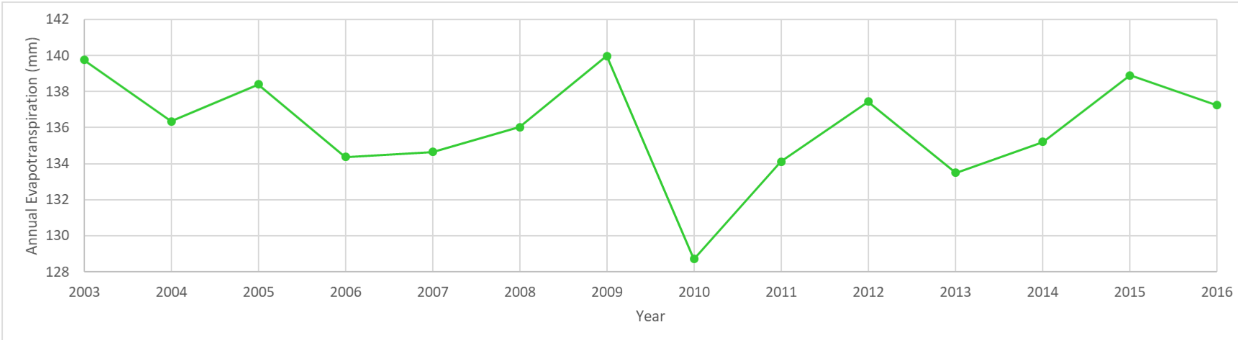

Figure 4-11: Annual ALEXI evapotranspiration from cultivated lands

Total annual evapotranspiration in this area ranged from 129 mm to 140 mm, with an average of 136 mm. This equates to an average of approximately 0.02 km^3 of evapotranspiration across this cultivated area, a very small amount relative to the total evapotranspiration in the basin. Furthermore, based on these data, it does not appear that ALEXI evapotranspiration levels spiked at any time near 2013, indicating that the newly implemented irrigation developments may not yet be affecting the water balance in the basin.

5. CONCLUSIONS

The objective of this study was to characterize the effect that Ethiopia's Gilgel Gibe III Dam may be having on Kenya's Lake Turkana. This was accomplished by first analyzing how Lake Turkana's water levels have changed since construction of the Gibe III Dam. I looked at both trends in overall volume and modifications of seasonal flood patterns. To deduce whether these observed changes in lake volume were caused by the basin's natural hydrology or manmade impacts, I conducted a basin-scale naturalized water balance to determine the expected lake volume alteration under natural conditions. I then assessed the filling of Gibe III reservoir, and subsequent controlled release patterns of the dam from satellite altimetry data. Lastly, I assessed the current extent and potential hydrologic impact of irrigation in the Omo River valley.

During the filling of the Gibe III reservoir through the end of 2015, Lake Turkana water levels saw a cessation of distinct annual floods and a general decline in water levels until mid-2017. From mid-2017 through 2018, lake levels were on the rise, and began to again display annual peaks, albeit less pronounced than pre-dam conditions. These annual peaks also occur approximately 4 months earlier than typical peaks seen in pre-dam conditions.

According to the water balance, approximately 7.2 km^3 of water was unaccounted for in the basin in 2015. This indicates that the filling of the Gibe III reservoir likely had a significant effect on Lake Turkana water levels. However, the water balance for 2015 also indicated 2015 was a relatively dry year, with a predicted lake volume loss of 3.1 km^3. This demonstrates that climatic conditions as well as dam filling likely caused the drop in lake levels. Although Lake Turkana lost 1.7 km^3 in 2016, this amount was much less than the predicted loss from the water balance, 7.6 km^3. Looking to the water level trend in the Gibe III reservoir, the dam only held back 25 m of water in 2016, compared with between 30 and 40 m typically seen in other years of operation. In 2017, there was agreement between the predicted and observed lake volume variation, indicating little manmade impact in the basin. In 2018, similar to 2015, there was a significant amount of water unaccounted for in the basin (6.5 km^3). However, in 2018, there was a net release of 10 m from the dam. This indicates that there may be additional factors in the basin affecting the water balance.

Although it has been reported that the Gibe III reservoir will support over 100,000 hectares (1,000 km^2) of irrigated land in the Omo River valley, only 16,000 hectares (160 km^2) of land is reported to be currently under cultivation (Sugar Corporation, 2019). This has been confirmed via inspection of aerial imagery for this study, which found approximately 130 km^2 of visibly cultivated land in the lower Omo River valley. Evapotranspiration signal from the ALEXI model showed that this development is not yet having a detectable water demand compared with basin-scale climatic trends.

The post-dam annual floods in Lake Turkana appear, on average, four months earlier than historical floods. These floods are also smaller in magnitude, but this may be attributed to climatic conditions and not to the dam. Based on water surface elevation levels in the Gibe III reservoir, the dam appears to be having controlled annual releases from December to June that lower water levels in the reservoir by about 40 m. Likewise, from June to November, water behind the Gibe III reservoir is held back. This artificial change in flow regime could potentially be contributing to the change in timing of annual floods from August through October to April through May.

There are many challenges and limitations associated with basin-scale hydrological studies, especially those using exclusively satellite-derived data and models. First, there is a limited amount of data available. Without stream discharge data from in situ gages, the boundaries of the water balance must be extended to the entire basin, instead of just the lake itself. Additionally, the most recent available bathymetric data for Lake Turkana is from the mid-1970s, making it infeasible to determine a reliable stage-storage curve for the lake. The second major limitation of this study is the high level of uncertainty in satellite-derived data. The uncertainties in basin-wide parameters compound in the resulting water balance, leading to very high levels of error in the final predicted lake storage change.

Although Gilgel Gibe III Dam appears to have an effect on the timing of seasonal floods, it does not yet appear to be causing substantial drops in lake levels. However, only three years have passed since construction of the dam, and both Lake Turkana and the Gilgel Gibe III reservoir should be monitored in future years to determine what long-term effects the dam may be having on the lake. In the future, a stage-storage curve could be developed for the Gibe III reservoir to determine the actual volume of water abstracted and released each year by the dam. In addition, there are currently plans to construct new dams in the Omo River basin, which may have an impact on Lake Turkana. These series of dams and reservoirs may also accelerate agricultural developments in the basin. Although there is currently a negligible irrigation signal in the Omo River valley, this may change when larger-scale agricultural production is implemented.

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Jessica (Jessie) Spruill is a Master of Science in Engineering candidate in the Johns Hopkins Department of Environmental Health and Engineering. Her degree is in environmental engineering with a focus in water resources. In 2015, Jessie graduated from Georgia Institute of Technology with a Bachelor of Science in Environmental Engineering. Following graduation, Jessie worked as a water resource engineer at the global engineering firm, CH2M Hill (now known as Jacobs Engineering), from 2015 to 2017. Jessie has also worked on international development projects in Uganda and Cambodia.